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Accelerated Soil erosion as a source of atmospheric CO_2

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ABSTRACT

Soil erosion, physical transport of soil over the landscape by alluvial and aeolian processes as source of energy, has a strong impact on the global carbon cycle (GCC). Being a light fraction (bulk density of 0.6–0.8 Mg/m^3) and concentrated in vicinity of soil surface, soil organic carbon (SOC) is preferentially removed by water and wind erosion. The process of erosion and the attendant transport of SOC are accelerated by conversion of natural to agroecosystems. Whereas the human-induced acceleration of soil erosion has depleted the SOC stock of agroecosystems, the fate of SOC transported over the landscape and that deposited in depressional sites is not understood. While a fraction of SOC transported to and buried under aquatic ecosystems (e.g., flood plains, lakes, ocean) may be protected because of limited microbial activity, labile fractions of SOC being transported over the landscape enroute to the depositional site are vulnerable to decomposition. Depending on the site-specific conditions with regards to the hydrothermal regimes and the degree of aeration, the decomposition may lead to emission of CO_2 under aerobic environments, CH_4 under anaerobic conditions, and N_2O under both situations. The process of soil erosion, especially that by water, is a 4-stage process: (i) detachment, (ii) splash, (iii) transport and redistribution, and (iv) deposition. Breakdown of aggregates, during the first three stages, exposes the hitherto encapsulated SOC to microbial processes and exacerbates its vulnerability to decomposition. Thus, the fate of SOC subject to erosion must be assessed for all landscape positions and integrated over the watershed. Lack of credible data regarding the fate of SOC at different erosional stages is a major cause of uncertainties. Thus, well-planned research at a watershed-level is needed to assess the impacts of erosional processes on decomposition of SOC, gaseous emission, and the soil/ecosystem C budget for diverse soils and management systems in global biomes/ecoregions. The data on global C budget is incomplete without consideration of the impact of erosion on SOC and the attendant gaseous emissions.

1. Introduction

Interest in research on soil organic carbon (SOC) and its dynamics has increased following the declaration of "4 per Thousand" program at COP21 in Paris (Lal, 2015). Land use change (LUC) from natural to managed ecosystems and soil degradation processes (e.g., erosion, nutrient depletion, salinization, decline of soil structure) have a strong impact on the global carbon cycle (GCC) because of the depletion of the SOC stock and the attendant emission of greenhouse gases (GHGs). The magnitude of SOC decline following LUC may be 20% or more even within the first 2 to 5 years (Mann, 1985, 1986; Kirschbaum et al., 2008; Luo et al., 2010; Olson et al., 2011, 2012) and considerably more in the tropics than that in soils of the temperate regions. The effects of erosion-induced transport of C are not accounted for in the global C budget (GCB). While the estimations vary widely, erosion-induced changes in global C budget (Le Quéré et al., 2016) must not be ignored (Lal et al., 2004, 2003; Chappell and Baldock, 2016). The loss of SOC is even more in soils prone to accelerated erosion (when the rate of erosion in managed ecosystems exceeds the rate of new soil formation) by land use and management systems which leave the soil unprotected against climatic erosivity (e.g., ploughed and bare soil surface) (Lal, 1992, 2003). Therefore, a positive response of conservation agriculture (CA) to C storage in surface layer may partly be due to reduction in erosion-induced transport of SOC (Li et al., 2016). Furthermore, the effects of erosion are exacerbated by changes in soil temperature and moisture regimes because of the LUC and subsequent plow-based management for row crops. In European agricultural soils, Lugato et al. (2016) reported that erosion-induced SOC fluxes were in the same order as the current gains from improved management and must be reduced to maintain soil health and productivity. Some examples of the estimate of SOC transport by erosional process are shown in Table 1.

In China, Yue et al. (2016) reported that water erosion displaced 180 ± 80 Tg C/yr between 1995 and 2015. Over grazing also exacerbates the erosional processes on grasslands and depletes the SOC stock (Mchunu and Chaplot, 2012). Degradation of pastures by woody encroachment and accelerated erosion can deplete the SOC stock even of dryland soils (Puttock et al., 2014). In California, USA, Yoo et al. (2005) observed that average SOC erosion rates from convex slopes were 1.4 to 8.0 g C/m^2 per year. Lal (2003) estimated the global erosion-induced displacement of SOC at 5.7 Pg C/yr of this 4.0 Pg C is redistributed and redeposited over the landscape, 1.14 Pg C emitted into the atmosphere and 0.57 Pg C is transported into the ocean. Walling (2009) reported

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Table 1
Examples of the magnitude of erosion-induced displacement of soil organic carbon.

Country	Type of Erosion	SOC Displaced	Reference
Australia	Water/wind	0.3-1.0 Pg C/yr	Chappell and Baldock (2016)
China	Wind	75 Tg C/yr	Yan et al. (2005)
China	Water	180 ± 80 Tg C/yr	Yue et al. (2016)
USA (California)	Water	1.4-8.0g C/m^2.yr	Yoo et al. (2005)
Global	Water	5.7 Pg C/yr	Lal (2003)

the annual global sediment flux of 36.6 Pg in the absence of reservoirs and dams. Assuming the sediment delivery ratio of 10%, sediment SOC concentration of 1%, and emission rate of 20%, erosion-induced emissions based on 36.6 Pg of sediment may be as much as 0.72 Pg C/yr. Such a magnitude of C emission cannot be ignored and must be accounted for.

Yan et al. (2005) estimated the loss of SOC by wind erosion in China at 75 Tg C/yr during 1990s, and the loss adversely affected NPP. The SOC being the most important indicator of soil quality (Rajan et al., 2010), erosion-induced loss of SOC affects soil quality on-site and the environment quality off-site (see Section #7). Chappell et al. (2014) assessed SOC erosion across Australia from 1950s to 1990 at 4 Tg SOC/yr, or loss of ~2% of SOC stock in 0–10 cm depth. Assuming complete mineralization, erosion-induced CO_2 emission would be 15 Tg CO_2 eq/yr. In a follow up study, Chappell and Baldock (2016) estimated the yearly amount of SOC that got transported due to erosion at 0.3–1.0 PgC/yr.

Regardless of its strong impact on the GCC, the fate of SOC transported by erosion remains poorly understood and full of uncertainties (Lal et al., 2004). The uncertainty is perpetuated by the lack of: (1) understanding of the impacts of erosional processes on temporal scale of short-term (years to decades) vs. long-term (centennial and millennial period), (2) data obtained at a range of spatial scales ranging from landscape to river basins, (3) knowledge about the transport of particulate organic carbon (POC) and of other fractions absorbed on clay surfaces into the depositional sites, (4) site-specific data on diverse environments (e.g., temperature, moisture, aeration, microbial community) at the burial site, (5) information about the degree of disconnect between buried carbon from the atmosphere, and (6) data regarding the fate of transported POC enroute to depositional site. The uncertainty is aggravated by the discrepancy in estimating the fate of in-transit fractions of SOC in generating and emitting not only CO_2 but also CH_4 and N_2O (Worrall et al., 2016). Yet, global flux of biospheric and the rock-derived (petrogenic) organic carbon to the burial in oceanic sediments is estimated at 157 and 43 TgC/yr, respectively (Galy et al., 2015). On a millennial timescale, this burial of C has an important impact on the GCC.

The fate of erosion-induced transport of SOC depends on several factors including the type of erosion, stage of erosion and the fractions transported. There are different types of erosion (Fig. 1) including that by water, wind, gravity, plowing, vertical and thermal. The dynamics of SOC is of specific interest in SOC transported by inter-rill/rill erosion, wind erosion, vertical erosion and the thermal erosion. The inter-rill erosion is a selective process which entrains primary particles. In contrast, rill erosion is non-selective and entrains aggregates and the particulate organic matter (POM) that is encapsulated within aggregates (Wilken et al., 2017). The thermal erosion is important in Cryosols or soils of the permafrost prone to thawing under the projected climate change. In addition, thermal erosion disturbance by thawing of Arctic Tundra represents a major ecosystem C loss (Pearce et al., 2015). Preferential burial of permafrost-derived SOC in Siberian-Arctic shelf waters (Vonk et al., 2014) can protect it against thawing-induced mineralization. The SOC stock is also affected by erosion caused by the wet snow avalanches in Alpine regions (Korup and Rixen, 2014).

Soil erosion by water (inter-rill/rill erosion) is a 4-stage process (Lal et al., 2004): i) detachment, ii) splash, iii) transport and redistribution over the landscape, and iv) deposition and burial at depressional/aquatic sites. Whereas aggregation leads to encapsulation of SOC/POC and protects it against the microbial processes; detachment, breakdown of aggregates, and splash expose the hitherto encapsulated SOC/POC and makes it vulnerable to decomposition. In general, SOC is prone to enhanced decomposition during the first three stages of the erosional process. However, the rate of mineralization may be slower during the depositional/burial stage, depending on the hydro-thermal regime and the depth of deposition (Fig. 2). Further, predominantly anaerobic conditions can accentuate methanogenesis leading to emission of CH_4 and to denitrification/nitrification processes causing the emission of N_2O. Thus, accelerated erosion can lead to increase in emission of all three gases (CO_2, CH_4 and N_2O) with an overall increase in the radiative forcing. There is a lack of scientific data on quantitative assessment of the gaseous emission at different erosional stages corresponding with different landscape positions. Soil erosion by water transports different fractions of C. Specific size fractions transported by inter-rill erosion must be identified (Wang et al., 2013), and their role on CO_2 emission quantified (Wang et al., 2014). Different fractions transported include POC, particulate inorganic C (PIC), dissolved organic C (DOC), dissolved inorganic C (DIC), dissolved CO_2-C, dissolved CH_4-C, mineral-associated organic C (MOC) and SOC encapsulated within aggregates. Specific rates of transport of these fractions vary among land use and management (Nachimuthu and Hulugalle, 2016). Hua et al. (2016) observed from a lysimetric study that SOC was mainly lost as MOC and DOC, and conservation practices must be adopted to minimize these losses.

The impact of erosional processes on SOC dynamics differs in relation to: (i) on-site, redistributional site, and depositional site, (ii) fraction of SOC (particulate, dissolved), and (iii) specific protection mechanisms (i.e., physical, chemical, biological). The process is further confounded by land use and the management. Above all, the controlling factors include: (i) breakdown of aggregates, (ii) net primary productivity (NPP) leading to the dynamic replacement, and (iii) changes in mineralization during the transport and deposition (Kirkels et al., 2014). Scientific information on the site-specific processes and the controlling factors is needed to assess whether erosion is a source or sink. Therefore, the objective of this chapter is to deliberate the impact of erosion-induced transport of SOC as a source or sink of atmospheric CO_2 and other GHGs, and identify research and development priorities to reduce the erosion-induced emissions of GHGs.

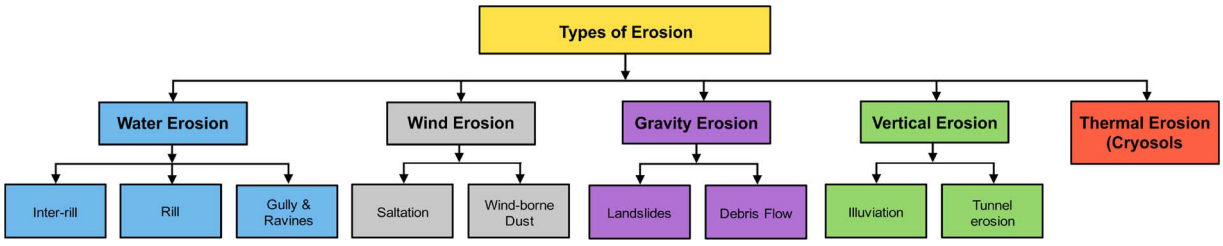

Fig. 1. Different types of erosion differently affect SOC transport (see text for explanation).

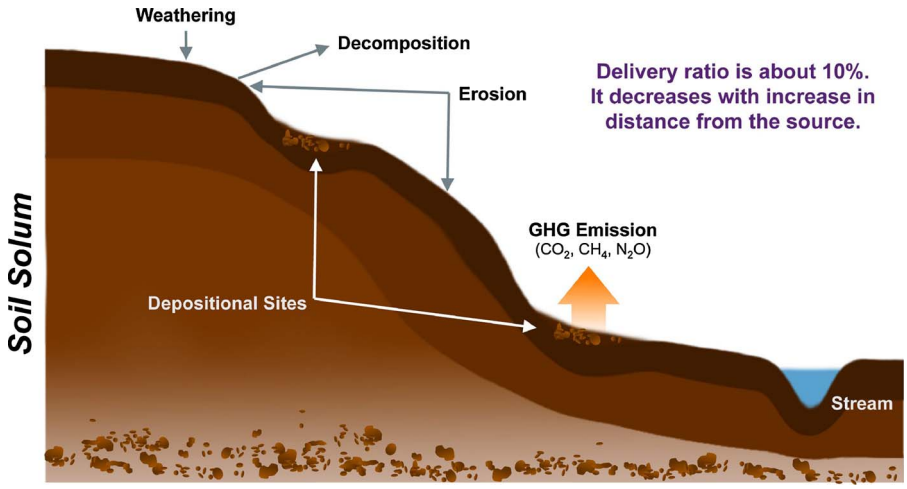

Fig. 2. Transport, redistribution, deposition and decomposition of soil organic matter transported by erosional processes leading to CO-C emission of ~1.1 PgC/yr. These estimates do not include CO_2 equivalent of CH_4 and N_2O emission caused by accelerated erosion (Lal, 2003).

2. Emission of greenhouse gases during erosional processes

Accelerated soil erosion sets-in-motion the processes which affects the soil/ecosystem C budget. It leads to disruption of aggregates and exposure of SOC to climatic elements and microbial enzymes. Physically unprotected POC and DOC fractions are prone to microbial decomposition (Dungait et al., 2012) and emitted into the atmosphere as CO_2 along with CH_4 and N_2O. The fate of SOC, emission or accretion, at a depositional site depends on: (i) the form of SOC being transported (e.g., SOC, POC, MOC; Józsa et al., 2014), (ii) the carbon enrichment ratio (CER), and (iii) the stabilization mechanisms at the depositional site. The fluxes of DOC from agroecosystems have been increasing since the intensification and high use of inputs (e.g., manure, plant residues, fertilizers), along with the effects of global warming. Some examples of the gaseous flux from erosion-induced transport of SOC are listed in Table 1.

A study on the fluvial flux of POC from the U.K. (Worrall et al., 2016) indicated that accelerated soil erosion is a net source of GHGs. The median emission factor was estimated at 5.5, 4.4 and 0.3 Mg CO_2 eq/yr for 1 Mg of fluvial C erosion, gross C erosion and gross soil erosion, respectively. Worrall et al., 2016 opined that gross soil erosion in U.K. would be a net sink of both C and GHGs if the following criteria were met: (i) the gross soil erosion rate were < 91 Mg/km^2.yr, (ii) the eroded C were completely replaced by new SOM, and (iii) if less than half of the gross emission made it into the stream network. In addition to loss of SOC/POC, loss of N with soil erosion is another important factor that impacts nitrification/denitrification processes that emit N_2O from eroded and buried sediments.

In general, the eroded material has a high CER since it is preferentially removed because of its low density (0.6–0.8 Mg/m^3) and that it is concentrated in vicinity of soil surface. High CER has been reported for eroded sediments from soils of the tropics (Lal, 1976a; Wan and El-Swaify, 1998) and temperate regions (Schiettecatte et al., 2008). Among several factors, the CER also depends on slope length, and decreases with increase in slope length (Müller-Nedebock et al., 2016). The CER also decreases with increase in the magnitude of soil loss and increase in the slope length (Lal, 1976b). Thus, soils prone to erosion are depleted of their SOC stocks. Wang et al. (2014) observed the sediment CER of 1.3–4.0 and loss of SOC by erosion both as POC and mineral-associated organic C (MOC), and that eroded fluxes of SOC as particles were 18 times larger than SOC fluxes. A study on assessment of soil C and N erosion from eight catchments in southern Sierra Nevada, California from 2005 to 2011 by Stacy et al. (2015) indicated that loss in sediments ranged from 0.025 to 4.2 kg/ha for SOC and that of 0.001 to 0.04 kg/ha for N. It is the loss of N along with that C that leads to emission of N_2O from sediments. Wind erosion also depletes SOC stock on site by preferentially removing POC and MOC, and Similar to rill/inter-rill erosion, wind erosion (saltation and dust transport) also have a high CER (Wang et al., 2013).

Stabilization of SOC at the depositional site is another determinant of gaseous emission (Wang et al., 2014). The SOC at depositional site can be protected by re-aggregation, deep burial and the prevalence of anaerobic conditions. Re-aggregation is strongly affected by clay + fine silt content and the nature of clay minerals. The higher the clay + silt content, the more is the physical protection. Further, re-aggregation is enhanced by the presence of 2:1 clay minerals.

3. Short coming of the global carbon budgeting by ignoring the selective loss of organic carbon by accelerated erosion

Gaseous emissions from soil occur at all stages of erosion, and from on-site and off-site locations. The schematics in Fig. 3 depict the complexity of erosion process at different stages and landscape positions. The amount of sediment transported, the CER, micro and meso-climate, factors affecting decomposition and mineralization must be understood at each stage for site-specific situations (Ni et al., 2012). A few examples of the data available are shown in Fig. 3 and systematic studies are needed at global scales, and coordinated for adoption of standardized methodology. Further, long-term research is also needed to determine the amount of eroded SOC eventually reaching depositional sites and open oceans, and to determine what fraction is emitted into the atmosphere. Important among other depositional sites, which strongly affect gaseous emissions (CO_2, CH_4, N_2O) include river flood plains, lakes and estuaries. Thus, neglecting the impact of erosional processes, is a short-coming of the data on GCB and estimates by modeling approaches (Chappell et al., 2014). Changes in SOC through erosion must be accounted for (Gaiser et al., 2008). Beneficial impacts of CA on SOC sequestration are also attributed to reduced losses of SOC by erosion. In some cases, erosion may also mask the effects of management practices (i.e., CA on SOC stocks; Chappell and Baldock, 2016).

4. The scaling issues: temporal and spatial

Both C and N compounds are subject to biochemical transformations even under aquatic and anaerobic environments with risks of emissions not only of CO_2 but also of CH_4 and N_2O. These biochemical processes of GHG emission depend on a range of complex and interacting processes which also depend on the nature of organic substances, depth of deposition, temperature regime and the degree of anaerobiosis. Despite

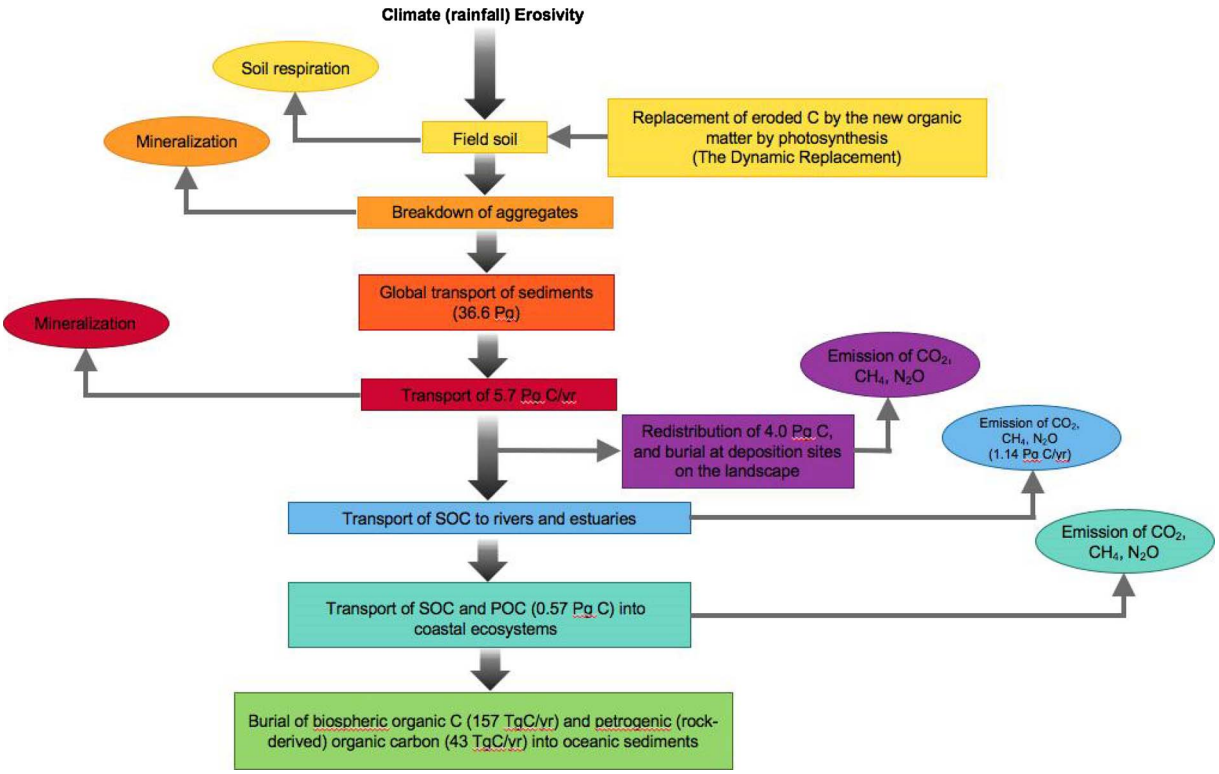

Fig. 3. A schematic of the multi-stage process of soil erosion, gaseous emission and deposition. Fate of soil carbon transported by erosion at different stages of an erosional process from on-site impact of climate erosivity to the burial of a small fraction (0.57 Pg out of 5.7 Pg transported) with the oceanic sediments. Soil erosion would be a net source if the on-site replacement of eroded C would be less than the new organic matter added through photosynthesis, and that all greenhouse gases (CO_2, CH_4, N_2O) were accounted for. The data on global transport of sediments are from Walling (2009), those on transport of SOC and emission enroute are from Lal (2003), and those on burial of biospheric and petrogenic organic C with oceanic sediments are from Galy et al. (2015). Beginning with the inter-rill/rill erosion through redistribution over the landscape and transporting to deposition and burial in aquatic ecosystems, the fate and pathways of C and associated N must be studied at different scales. The quantitative data, based on measurements of SOC transported into aquatic ecosystems at watershed scale is scanty. Even scantier is the emission of GHGs (CO_2, CH_4, N_2O) at different landscape units (summit, side slope, foot slope, etc.) within a watershed under managed and natural ecosystems.

uncertainties, global estimates of erosion-induced redistribution (~4 PgC/yr; Lal, 2003) and deposition (0.57 PgC/yr; Lal, 2003), cannot be ignored and must be considered in the GCB. Predicting the long-term fate of erosion-induced transport of SOC and associated N must be objectively assessed, because risks of soil erosion may be exacerbated with the projected climate change (Lee et al., 1996; Nearing et al., 2004). Specific climate-induced risks include: (i) increased frequency of intensive rainfall events generating significantly more runoff and soil erosion, and/or (ii) warmer (and drier) conditions, increasing evapotranspiration and hence, hampering plant growth and affecting the development of vegetation cover, and subsequently, increasing ecosystem's vulnerability.

Kirkels et al. (2014) suggested an eco-geomorphological approach to assessing the impacts of soil erosion. The proposed approach encompassed physical- and biological-driven strategy to specifically assess sources and sinks at a watershed-scale. Several complexities and uncertainties in determining the fate and pathways arise from a high spatio-temporal variability on processes across a wider range of scales (Kirkels et al., 2014). Processes differ at different scales: spatially (e.g., point, plot, landscape, and watershed) and temporally (annual/decadal vs. millennial/geological). Therefore, soil C budget must be assessed at a watershed scale, to encompass all of the four stages of the erosion-deposition process (e.g., detachment, breakdown, transport and redistribution, and deposition) to determine whether erosion's net effect is a source or sink of GHGs. Processes also differ temporally, short-term (annual/decadal) effects of anthropogenically accelerated driven erosion may be a net source of GHGs (CO_2, CH_4, N_2O). On a geological or millennial scale, burial of vegetationally-driven POC/MOC in marine sediments may make erosion a net sink (Galy et al., 2015). The "dynamic replacement" concept may be applicable on centennial or millennial (long-term) rather than an annual or a decadal scale (short-term), which requires additional research.

5. Factors affecting the fate of soil carbon transported by erosional processes

Scientific understanding of the fate of C being transported by erosional processes is poor, the process is complex and driven by a range of direct and indirect factors (Fig. 4). The apparent debate, whether soil erosion is a source or sink of C, is driven partly by the scarcity of experimental data and partly by the use of non-standardized terminology (whether the term erosion is used exclusively to denote the amount of SOC delivered at the outlet of watershed or inclusively involving all four phases of erosion and whether SOC loss is expressed in terms of the C per se or as CO_2 equivalent with due consideration of the GWP of CH_4 and N_2O). With focus only on the last of the four stages of erosion, erosion-induced burial of C with sediments in depositional sites and aquatic ecosystems is considered sequestration by sedimentologists (Van Oost et al., 2007; Berhe et al., 2008; Quine and Van Oost, 2007; Nadeu et al., 2012). The same arguments apply to the preferential burial of permafrost-derived organic C in Siberian-Arctic shelf waters (Vonk et al., 2014) and transport of black C (charcoal) in terrestrial and aquatic ecosystems (Forbes et al., 2006). Nonetheless, understanding the long-term fate of buried SOC in colluvial soils (Wang et al., 2015) is a researchable priority and must be addressed.

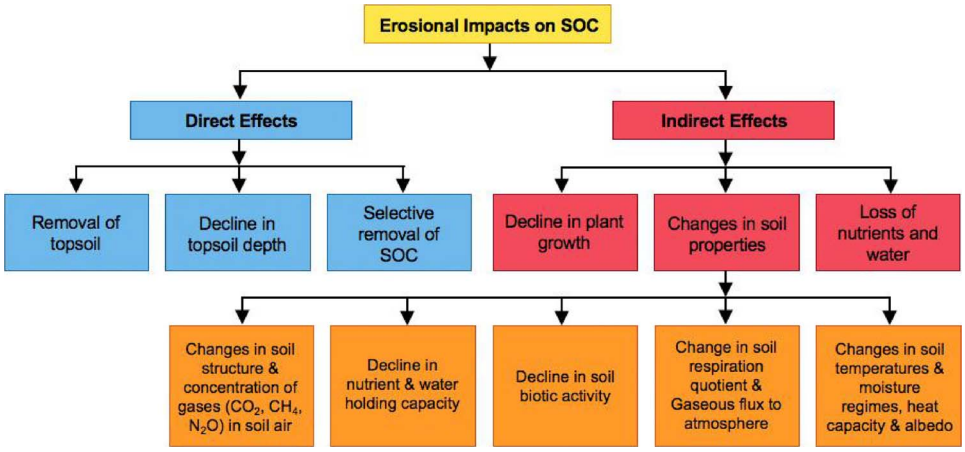

Fig. 4. Consequences of erosion-induced depletion of soil organic carbon by direct and indirect effects.

6. On-site and off-site effects of erosion-induced transport of SOC

Accelerated soil erosion has numerous on-site and off-site effects (Fig. 4). On-site, it leads to decline in soil health because of degradation of important soil properties and processes. Off-site, it leads to sedimentation of reservoirs and waterways, non-point source pollution, emission of GHGs and decline in quality of water and air. On-site, accelerated erosion strongly depletes SOC stock both by hydraulic and aeolian-driven processes (Fig. 5). These on-site impacts, exacerbated by the loss of SOC from the rootzone, adversely affect soil health, reduce use efficiency of inputs, decrease agronomic productivity, and minimize the input of biomass-C by dynamic replacement. The off-site effects pollute the environment (i.e., water, air and soil). Surface soil at the depositional sites can be buried by unproductive sediments. Depletion of SOC on-site is attributed to a range of direct and indirect effects of soil erosion. Directly, depletion of SOC stock is caused by removal of SOC as indicated by a high CER. Indirectly, depletion of SOC stock is caused by decline in plant growth and reduction in NPP, loss of nutrients and water, and changes in soil properties (Fig. 5). Notable among erosion-induced changes in soil properties include that in soil structure and composition of soil air, reduction in nutrients and water holding capacity, decline in activity and species diversity of soil biota, soil respiration quotient and gaseous flux to atmosphere, soil temperature and moisture regime caused by changes in heat capacity and albedo etc. Thus, NPP, use efficiency of inputs (e.g., fertilizers, amendments, irrigation) and return of biomass-C into the soil are drastically reduced. Given the complexity of the processes involved, more research is needed in order to test the validity and significance of the "dynamic replacement" concept within the global C-cycle sink-source question and the exact role soil erosion fulfills in pedological ecosystem C dynamics under changing land use and climate conditions.

7. Conclusion

Considering all 4 steps of the erosional process and global warming potential of all gases (including CH_4 and N_2O), accelerated erosion at watershed level and at short-term (annual, decadal) scale is a net source of greenhouse gases. The rate and extent of the source depend on land use, climate, soil properties and the relative amount of different components of eroded SOC (e.g., fluvial, gross C, gross soil erosion), and need additional research especially on checking the site-specific validity of the concept of "dynamic replacement."

Adoption of erosion-preventative measures is more relevant now than ever before because of the scarcity of prime agricultural soils, competing demands for agricultural soil resources (industrial, urban, recreational) and growing needs of the increasingly affluent world population.

Restoration of eroded soils and recarbonization of the biosphere, by afforestation of eroded (i.e., Shivalik hills of the lower Himalayas from Afghanistan to Cambodia) and desertified lands (i.e., West African Sahel) are also among important priorities because of the need for advancing food and nutritional security, adaptation and mitigation of climate change, improvement of the quality and renewability of water resources, and enhancement of the environment.

Impacts of accelerated erosion, on-site and off-site, must be assessed with due consideration to the soil and ecosystem C budget at watershed scale and expressed in terms of CO_2 equivalent with consideration of the GWP and CH_4 and N_2O emissions.

In addition to standardizing the terminology and methodology for assessments, the research must also focus on the on-site and off-site

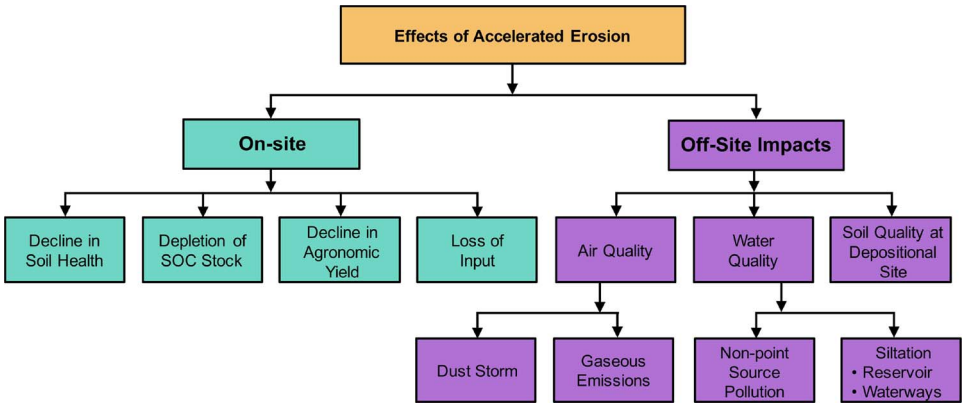

Fig. 5. The on-site and off-site impacts of accelerated erosion.

effects of erosional processes, the gross and net soil erosion rates, replacement of new SOC on the eroded sites, specific fraction of the loss of SOC (POC, DOC, or MOC), emission of all GHGs (CO_2, CH_4, N_2O) at different landscape units, and on-site vs. off-site impacts on NPP. The soil and ecosystem C budgets must be computed in terms of CO_2equivalent with due consideration to the GWP of different gases.

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